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ELECTROMAGNETIC CHARACTERISTICS OF LEVITATION MELTING WITH COLD CRUCIBLE①

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ABSTRACT By using the numerical simulation method with quasi-three-dimensions and the modified coupled current model presented in the previous work, the influences of the structure of cold crucible, the power frequency and the electricity property of melting charge on the electromagnetic field in the levitation melting processes were analyzed. The fundamentals for the technique design of levitation melting with cold crucible were presented. It is shown that the levitation melting with cold crucible is a self-balanced and self-stable process, and the cold crucible can be segmented 16 ~ 20 sectors for high frequency electromagnetic field and/or 4 ~ 8 sectors for lower frequency one. It is also shown that the change of the power frequency has great influence on the magnetic flux density on the surface of metallic charge, but for nonmetallic charge, the main influence on the magnetic flux density is the segmented number of cold crucible.

Key words cold crucible electromagnetic induction levitation melting numerical simulation

1 INTRODUCTION

Being widely used in metallurgy and new materials processing, the electromagnetic levitation melting with cold crucible is a valid method to manufacture the metal or nonmetal materials with high melting temperature, high purity, high activity and/or radioactivity[1,2]. Its working principle is:

(1) The melting material (charge) in the crucible is set in a high frequency electromagnetic field and is heated by electromagnetic induction.

(2) At the same time, the charge is levitated by the electromagnetic force induced in it, which results in the charge to be non-contacted with the crucible.

(3) In that process, the main way of heat transfer between charge and crucible is transformed from conduction to radiation, which largely reduces the heat loss rate, so that the charge can be heated to a very high temperature (up to 3 000 ℃) and without contamination.

To obtain more power efficiency and enough electromagnetic levitation force, the crucible structure must be designed specially. It must be able to make that the electromagnetic energy caused by the inductor (coils) with a high frequency current can be concentrated and penetrated into the limited capacity of cold crucible. And high electromagnetic flux density can be formed on the surface of the charge, so that the effectively electromagnetic levitation can be generated.

Levitation melting with cold crucible is a polytechnic technology that concerns several subjects about electromagnetism, induction heating, magnetohydrodynamics, heat transfer with phase change, mechanics, physicochemistry, metallurgy and technology. Its technical crux lies on the special structure of cold crucible and the optimization design of the electromagnetic field of levitation. Hence, to make the structure of cold crucible be of good characteristics of electromagnetic penetration and low eddy loss, and to make the charge obtain the high induction current and levitation force through the reasonable design of electromagnetic field, are con-

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cerned by many investigators[3-5].

Based on the previous studies[6-8], we utilize quasi-three dimensional model and the modified coupled current method to study the electromagnetic characteristics of levitation melting with cold crucibles, i.e. the coupled relations between the electromagnetic field intensity and distribution, and the electricity properties of melting materials (charge), the power frequency and the structure of cold crucible, etc., which are the foundations of optimization design for the special structure of cold crucible and the electromagnetic field of levitation melting processes.

2 ELECTROMAGNETIC MODEL OF LEVITATION MELTING WITH COLD CRUCIBLE

A cold crucible is schematically illustrated in Fig.1. Here the structure of cold crucible is segmented. This segmented structure of crucible enables the energy of source electromagnetic field to penetrate the cold crucible and to work on the charge. And it can largely reduce the induction eddy consume in the cold crucible. When alternating current is applied to the inductor (coils), the induction current will be generated in both the charge and cold crucible. This process can be equal to a transformer unloaded, in which the induction current in charge is similar to that of the secondary coils of this transformer. Hence a very large heat source can be generated to melt the charge and, in the same time, both the electromagnetic levitation and stirring for molten charge are formed. As the result of levitation, the charge and the crucible are non-contacted, and the way of heat transfer from charge to cold crucible is radiation, from which it is convenient to charge for getting high purity and temperature. And as the result of stirring, the charge is always homogeneous in the process of levitation melting with cold crucible. So, levitation melting with cold crucible is a process of energy transformation and reciprocity, in which the energy is transforming from electricity to magnetism, and then, to heat, to flow, and to force. In this process of energy transforming, the electromagnetic field is the key and the foundation.

According to electromagnetism, the equations of levitation melting with cold crucible can be described by:

$$\nabla \times \boldsymbol{E} = -\mathrm{j}\omega \boldsymbol{B} \quad \text{(Faraday's law)} \tag{1}$$

$$\nabla \times \boldsymbol{B} = \mu \boldsymbol{J} \quad \text{(Ampere's law)} \tag{2}$$

$$\nabla \cdot \boldsymbol{B} = 0 \quad \text{(Magnetic flux continuity law)} \tag{3}$$

$$\boldsymbol{J} = \sigma \boldsymbol{E} \quad \text{(Ohm's law)} \tag{4}$$

$$\nabla \cdot \boldsymbol{J} = 0 \quad \text{(Current continuity law)} \tag{5}$$

where the vectors $\boldsymbol{E}$, $\boldsymbol{B}$ and $\boldsymbol{J}$ are the complex intensity of electric field, complex density of magnetic flux, and complex density of current respectively; ω, μ and σ are the angular frequency of electromagnetic field, the permeability and conductivity of materials, and $\mathrm{j} = \sqrt{-1}$.

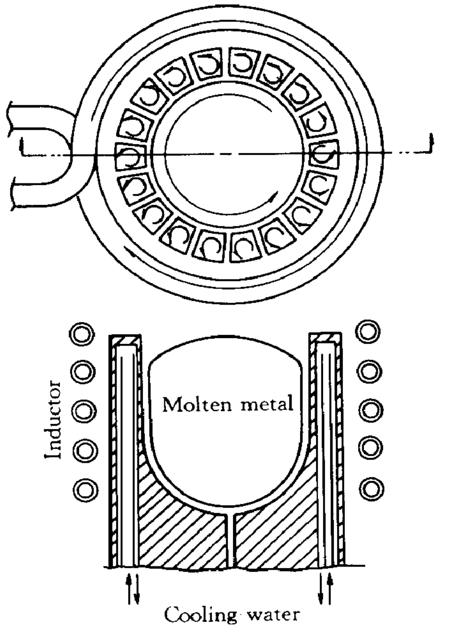

Fig.1 Principle and structure of cold crucible

Apply the complex vector potential $\boldsymbol{A}$ to above equations and let $\boldsymbol{B} = \nabla \times \boldsymbol{A}$ and $\nabla \cdot \boldsymbol{A} = 0$, then we can get

$$\boldsymbol{E} = -\mathrm{j}\omega \boldsymbol{A} - \nabla \Phi \tag{6}$$

and

$$\nabla^2 \boldsymbol{A} = -\mu \boldsymbol{J} \tag{7}$$

where Φ in Eqn.(6) is a complex scalar potential, which is nonzero only in the source zone, and $\boldsymbol{J}$ in Eqn.(7) includes all the source current and induction current.

Hence, above electromagnetic problem can be transformed into following integral equation:

$$J = -\frac{j\omega\mu\sigma}{4\pi}\int_{\Omega} J(r)\,d\Omega/|r'| - \sigma\nabla\Phi \quad (8)$$

where Ω consists of all the conductive zones. And then the following results can be calculated sequentially:

$$B = \frac{j}{\omega\sigma}\nabla\times J \quad (9)$$

$$F = Re(J\times B^{*})/2 \quad (10)$$

$$p_m = (B\cdot B^{*})/2\mu \quad (11)$$

where F is the electromagnetic force, which can be separated into both rotation and non-rotation parts, in which the rotation part makes the molten charge stir and the non-rotation one makes charge levitate; and p_m is the electromagnetic pressure on the charge surface; The mark '*' presents the conjugate complex and '*Re*' is the real part of the complex vector.

Utilizing the quasi-three dimensional electromagnetic model and the modified coupled current method presented in Ref.[8], the numerically discrete computation of electromagnetic field of levitation melting with cold crucible can be described to solve the complex linear equations:

$$([R]+j\omega[X])\{I\} = \{U\} \quad (12)$$

where $\{I\}$ is the unknown complex current vector which includes the total original and inducted current in the calculation zone, $\{U\}$ is the complex electric potential vector whose element is nonzero for the source zone only, $[R]$ is the diagonal resistance matrix, and $[X]$ is the full and symmetric inductance matrix, in which all the effects of three dimensionally segmented structure of cold crucible on the electromagnetic field of melting processes is involved. So the elements of $[X]$ can be written as

$$X_{ij} = \begin{cases} L_i & (i = j \text{ and } i \not\subset \Omega_t) \\ L_i + \sum_{k=1}^{n-1} M_{ii}^{(k)} & (i = j \text{ and } i \subset \Omega_t) \\ M_{ij} & (i \neq j \text{ and } j \not\subset \Omega_t) \\ \sum_{k=1}^{n} M_{ij}^{(k)} & (i \neq j \text{ and } j \subset \Omega_t) \end{cases}$$

$$(i, j = 1, 2, \ldots, m) \quad (13)$$

where L_i and M_{ij} are the self-inductance coefficient of i-th current circle and the mutual inductance coefficient between i-th and j-th current circles separately; Ω_t is the segmented zone of cold crucible, and both n and m are the segment number of cold crucible and the total number of current circles in the numerically discrete zone of computation, respectively.

Up to now, the numerical computation of quasi-three dimensional electromagnetic field of levitation melting with cold crucible can be carried out, and the solutions J, B, F and p_m can be solved sequentially from above equations (12), (9), (10) and (11).

3 NUMERICAL RESULTS AND ANALYSIS

During the levitation melting, the power frequency, the segmented structure of cold crucible and the electricity properties of charge can influence directly the effectiveness of electromagnetic induction and levitation of melting materials, the magnetic penetrability and the eddy loss of cold crucible. In this paper, the numerical analysis with the quasi-three dimensional electromagnetic model and the modified coupled current method from Ref.[8] is presented for a cold crucible system with an inner diameter 6 cm, melting space 0.14 L and the maximum levitation capacity 1 kg. The influences of the power frequency, the electricity properties of charge and the segmented structure of cold crucible on the intensity and distribution of electromagnetic field during the levitation melting are studied.

The numerical simulation shows that in the processes of levitation melting with cold crucible, magnetic flux B on the surface of molten charge is along the generatrix of melt and the induction current J of melt is along the azimuthal direction. Hence the electromagnetic force F is in the direction of inner normal vector of melt surface. The molten charge is pushed apart from the inner wall of cold crucible by the electromagnetic force. When the electromagnetic pressure of charge balances the hydrostatic one of that, the magnetic levitation is generated. The numerical result also shows that when the gap between the melt surface and the inner wall of cold crucible is decreased, the intensity of electromagnetic flux within the gap can reach a very high level. Thus the induction current and then the electromagnetic pressure on the melt surface can increase largely to push it inward. The levitation melting with cold crucible is a self-balanced and self-stable process.

In this paper, the influences of the power frequency and the segmented structure of cold crucible on the penetration of cold crucible are studied firstly.

Fig.2 illustrates the relations between the magnetic flux density $\boldsymbol{B}$ at point A (r/R = 0.65, Z/H = 0.45) on the charge surface and both the power frequency and the segment number of cold crucible. From this figure, it is shown that as the power frequency becomes high, the magnetic flux density on charge surface is decreased, and this tendency becomes more prominent when the frequency is over 100 kHz. This indicates that the electromagnetic field with a low frequency is easy to penetrate cold crucible. On the other hand, it is also shown that the less the segment number is, the more quickly the magnetic flux density decreases as the frequency increases from 10 to 250 kHz. For the cold crucibles with different numbers of segments (n = 4 ~ 24), it is shown that as the frequency increases from 10 to 250 kHz, the decreasing magnitude of magnetic flux density $\boldsymbol{B}$ at point A is from 28 %(for n = 4) to 5 %(for n = 24), but when the frequency is less than 10 kHz, the magnetic flux density isn't varying with the segment number of cold crucible for $4 \leqslant n \leqslant 24$. This means that the effect of decreasing the induction eddy loss of cold crucible itself by increasing the segment number of it, is efficient for higher frequency, but for lower frequency the cold crucible can be divided into 4 ~ 8 segments reasonably.

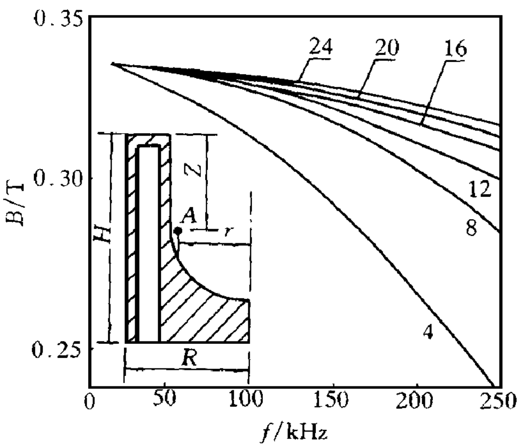

Fig.2 Relations between penetration and both frequency and segmented structure of cold crucible

Also in Fig.2 the calculation result presents the influence of changing the segment number of cold crucible on the magnetic flux density $\boldsymbol{B}$ at point A in the case of the power frequency to be 250 kHz. It is shown that if the magnetic flux density at point A for n = 4 is unity, it increases to 1.2 for n = 8, to 1.3 for n = 16, to 1.32 for n = 24, and then it is seldom increasing. Hence the segment number of cold crucible is reasonable within 16 to 20 for high frequency.

Secondly, the effect of electricity property of charge on the electromagnetic characteristics of levitation melting with cold crucible is studied.

Fig.3 illustrates the magnetic flux densities at point A, when the charges with conductivity (S/m) varying from 10^4(oxide materials) to 10^6 (metal and alloy materials) are melting in above mentioned cold crucible with the power frequency varying from 10 ~ 250 kHz. It can be seen from the figure that in the selected domain of power frequency, the surface magnetic flux density of charge has a decreasing tendency with the frequency increasing, and this tendency is speeding up with the conductivity of charge increasing. And from the figure, it is shown that for oxide materials ($\sigma = 10^4$ S/m), the changing magnitude of surface magnetic flux density of charge with the frequency isn't large, but for metal or alloy materials ($\sigma = 10^6$ S/m), it is decreased largely. This shows that for magnetic levitation melting with cold crucible, it is convenient to oxide materials with higher frequency, and to metal or alloy materials, it is convenient with lower frequency.

And it can be seen from the figure that for the charges with the same conductivity, the surface magnetic flux densities are decreasing with the increase of the power frequency, and finally tend to a stable value. This means that the magnetic flux on the charge surface is the interacting results of both the source magnetic field and the

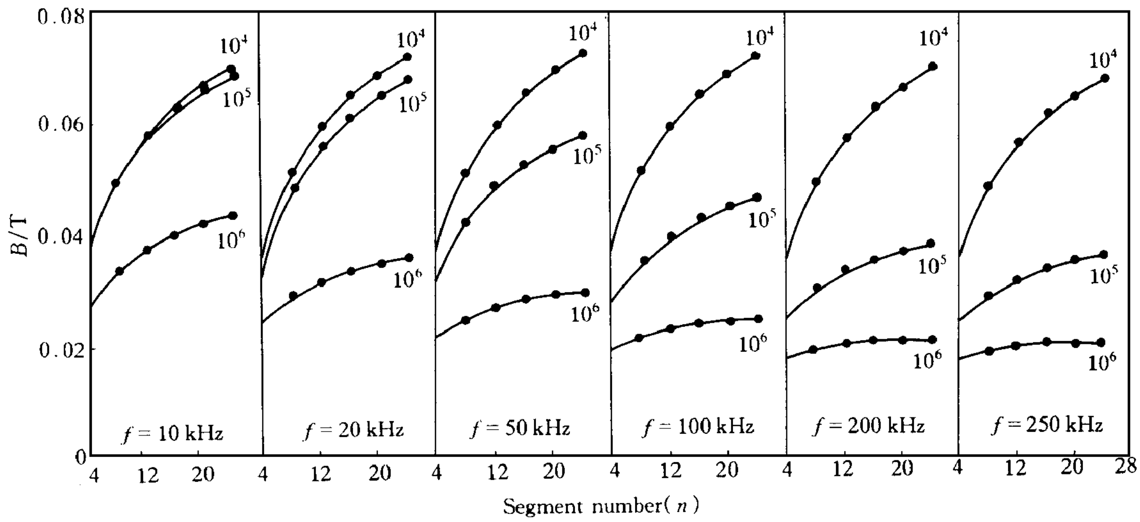

Fig.3 Influences of frequency, conductivity and segmented structure on EM field in levitation melting

inducted one in the change itself and the cold crucible. And higher conductivity of charge leads to stronger inducted current and then stronger inducted electromagnetic field in the inverse direction with the source ones. Homogeneously, higher power frequency leads to more obvious skin effect, which influences on both the distribution of induction current in the charge and the intensity of magnetic flux density on the surface greatly. When the power frequency is higher enough, the induction current of charge will turn to surface current and then, the surface magnetic flux density of charge will tend to a stable value.

Additionally, for every presented frequency, the surface magnetic flux density of charge is becoming higher with the increasing of the segment number of cold crucible, but this rising tendency is gradually slowed down, and the higher the frequency and the conductivity are, the larger the slowing magnitude of this tendency is. It can be seen from the figure that the more the segment number of cold crucible is, the higher the surface magnetic flux density of charge is. But the higher the conductivity of charge is, the weaker the effect of the segment number of cold crucible on the surface magnetic flux density is, relatively. Hence to change the power frequency and/or the segment number of cold crucible can be just the same to change the surface magnetic flux density of charge. For oxide charges, the influence of the segmented structure of cold crucible on the melting electromagnetic field is greater than that of power frequency, and for metal or alloy charges with high conductivity, the influence of power frequency on that is more important. When the power frequency is presented, the surface magnetic flux density of metal charges is dependent on the induction current and electromagnetic field in itself, which is relative to the power frequency greatly, and that of oxide charges is dependent on the induction current and electromagnetic field in cold crucible, which is relative to the segmented structure of cold crucible directly.

Finally the influence of gap of the segmented structure of cold crucible on the surface magnetic flux density at point A is illustrated in Fig. 4, where K means the increasing ratio of the surface magnetic flux density compared with that when the gap width $d = 0.1$ mm. In this paper, the results of numerical simulation for electromagnetic field in the processes of levitation melting with cold crucible indicate that when the gap width is changed from 0.1 mm to 2.0 mm, the average increase of the magnetic flux density in the melting space is about 2 %, but it is concentrated on the slits of cold crucible, where it can be seen that the molten charge is pushed inward in the experiments. In Fig.4 it is shown that the surface magnetic flux density of charge is rising with the increase of gap width between two segments, and the more the quantity of the segments is, the more obvious the rising magnitude is. On the other hand, the numerical result shows that the rising ratio of the surface magnetic flux density of charge caused by the increasing of gap width between two segments of cold crucible is only relative to the segment number. It is seldom relative to the power frequency and the conductivity of charge.

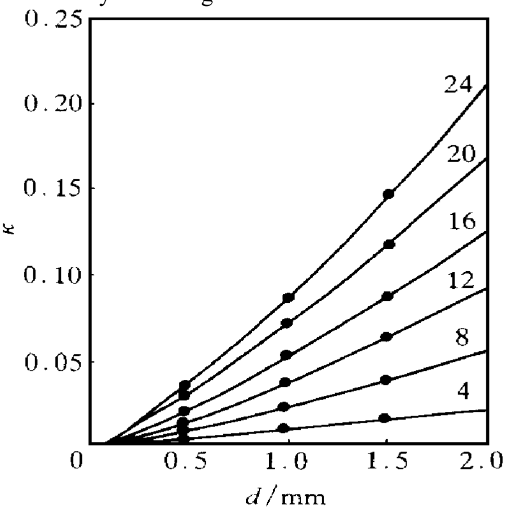

Fig.4 Influence of gap between segments on surface magnetic flux density of charge

4 CONCLUSIONS

(1) The levitation melting with cold crucible is a self-balanced and self-stable process, in which the surface magnetic flux density of charge is related to the conductivity of charge, the power frequency, the segment number and the gaps between segments of cold crucible.

(2) The segmented structure of cold crucible decreases the eddy current consumed by cold crucible itself, and the higher the power frequency is, the more obvious the effect of segmented structure of that on decreasing eddy loss is. Hence, the segment number of cold crucible is reasonable in the domain of 16 ~ 20 for higher power frequency, and it should be 4 ~ 8 for lower power frequency.

(3) In the processes of levitation melting with cold crucible, the influence of power frequency on magnetic flux density in the melting space is very large. The magnetic flux density in melting space is decreasing with the rising of power frequency, and this tendency is increasing when the frequency becomes higher than 100 kHz.

(4) For every charge presented conductivity, its surface magnetic flux density is rising with the segment number of cold crucible increasing, and decreasing with the power frequency rising. Here, to change the power frequency is effective largely on the surface magnetic flux density for metal charge, but for oxide charge, the important factor is the segment number of cold crucible.

(5) To increase the gap width between two segments of cold crucible will rise the surface magnetic flux density of charge at the positions corresponding to the slits in cold crucible, and the more the quantity of segments is, the larger the rising magnitude of that is.

(6) The rising magnitude of surface magnetic flux density of charge caused by increasing of gap width between two segments of cold crucible is seldom relative to the power frequency and the conductivity of charge.

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